
*Carnegie Observatories Astrophysics Series, Vol. 5:
RR Lyrae Stars, Metal-Poor Stars, and the Galaxy
ed. A. McWilliam (Pasadena: Carnegie Observatories)*

Mapping the Galactic Halo with SDSS, LINEAR and PTF RR Lyrae Stars

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Abstract

We present an analysis of Galactic halo structure and substructure traced by ~ 500 RR Lyrae stars in the SDSS stripe 82 region. The main result of this study is a 2D map of the Galactic halo that reaches distances of 100 kpc and traces previously known and new halo substructures, such as the Sagittarius and Pisces tidal streams. We also present strong direct evidence, based on both RR Lyrae and main sequence stars, that the halo stellar number density profile significantly steepens beyond 30 kpc from the Galactic center. Using a novel photometric metallicity method that simultaneously combines data for RR Lyrae and main sequence stars, we show that the median metallicity of the Sagittarius trailing stream in the SDSS stripe 82 region is $[\text{Fe}/\text{H}] = -1.2 \pm 0.1$ dex. In addition to these results, we will present ongoing work on a 3D map of the Galactic halo constructed using a sample of ~ 4000 RR Lyrae stars that covers 8500 deg^2 of northern sky and probes up to 30 kpc from the Sun.

1. Galactic Halo as the Rosetta Stone for Galaxy Formation

Studies of the Galactic halo can help constrain the formation history of the Milky Way and the galaxy formation process in general. For example, state-of-the-art simulations of galaxy formation predict numerous substructures, such as tidal tails and streams, in halos of Milky Way-size galaxies (e.g., see Fig. 14 in Johnston et al. 2008 or Fig. 6 in Cooper et al. 2010). The amount, morphology, kinematics, and chemical composition of these substructures depend on the accretion history of the simulated galaxy (Johnston et al. 2008; Cooper et al. 2010). Therefore, if we map the substructures in the Galactic halo and compare the resultant maps with simulations, we will

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be able to constrain the formation history of the Milky Way.

Maps of the Galactic halo that probe galactocentric distances (R_{GC}) of $\sim 20 - 30$ kpc have already been made using near turn-off main sequence stars (Jurić et al. 2008; Bell et al. 2008) selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000). Unfortunately, the largest discrepancy between simulated halos with different formation histories occurs at distances beyond 30 kpc (e.g., compare panels in Cooper et al. 2010 Fig. 6). Therefore, to discriminate between different formation histories we need to map the Galactic halo beyond 30 kpc and to do that we need to use tracers that are brighter than main-sequence turnoff stars.

2. Mapping the Galactic Halo with SDSS Stripe 82 RR Lyrae Stars

To map the Galactic halo beyond 30 kpc, we used RR Lyrae stars selected from the SDSS stripe 82 region ($20^h32^m < \alpha_{J2000.0} < 04^h00^m$, $-1.26^\circ < \delta_{J2000.0} < +1.26^\circ$, $\sim 280 \text{ deg}^2$). This region has been repeatedly observed during SDSS-I and SDSS-II parts of the survey and on average, there are about 30 observations per source. The photometric precision of SDSS Stripe 82 data is ~ 0.02 mag at the bright end ($r < 18$) and ~ 0.05 mag at $r \sim 21$ (Sesar et al. 2007). For comparison, the apparent magnitude of an RR Lyrae star at 100 kpc is $r \sim 21$.

The candidate RR Lyrae stars were pre-selected using SDSS colors and using some low-level variability statistics, such as rms scatter and chi-square per degree of freedom (for details on the selection algorithm see Sesar et al. 2010a). The period of variability was found for each candidate using an implementation of the *Supersmoothen* algorithm (Reimann 1994), the candidate light curve was folded using that period and a custom set of ugriz template light curves was fitted to the period-folded light curve for identification. In total, we have identified about 400 type-*ab* (RRab) and about 100 type-*c* (RRc) RR Lyrae stars in the SDSS stripe 82 region.

To calculate distances for RRab stars we used the Chaboyer (1999) $M_V - [Fe/H]$ relation

$$M_V = (0.23 \pm 0.04)[Fe/H] + (0.93 \pm 0.12) \quad (1)$$

and assumed $[Fe/H] = -1.5$ dex (median halo metallicity; Ivezić et al. 2008) as the metallicity of all RR Lyrae stars in our sample¹. This relation gives $M_V = 0.6$ for the absolute magnitude of RRab stars in the Johnson *V* band. The resulting fractional uncertainty in distance due to unknown metallicity, evolutionary effects, and photometry is $\sim 5\%$. RRc stars were not used in the rest of this study.

A Bayesian number density estimator (Ivezić et al. 2005) was applied on the spatial distribution of RR Lyrae stars and the calculated number densities of RR Lyrae stars were compared to values predicted by a smooth, oblate halo model with a density

¹ Spectroscopic metallicities were not available for the majority of stars in our sample.

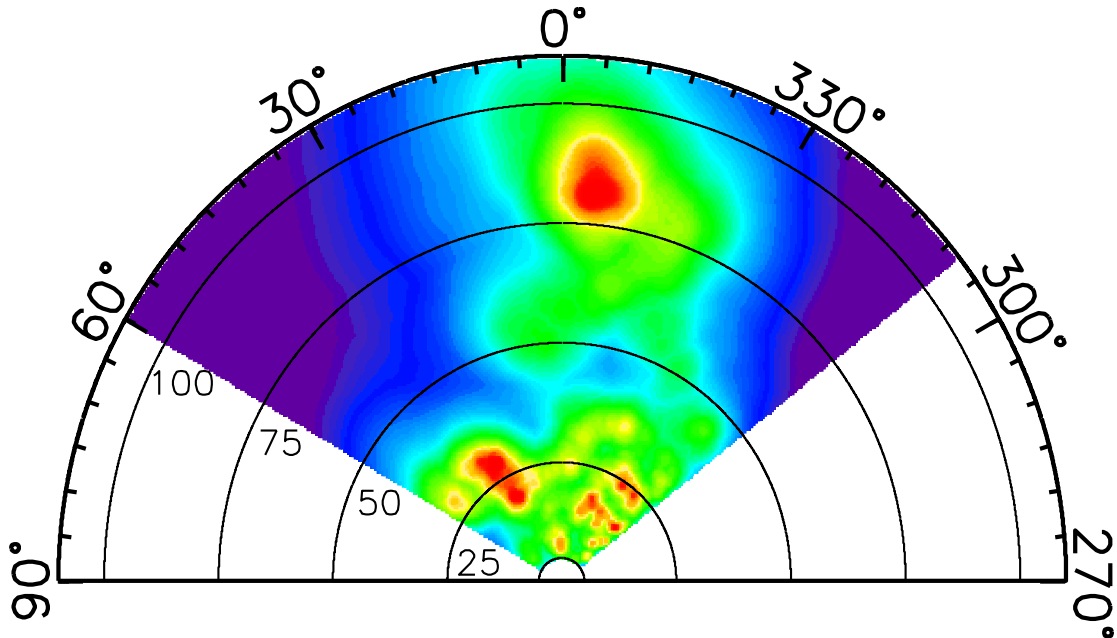


Figure 1.— Halo substructures traced by RR Lyrae stars in SDSS stripe 82. The heliocentric distance in kpc is in the radial direction and angle indicates equatorial right ascension. The red color indicates substructures, green color shows the smooth halo, and the blue color shows regions where there are almost no stars. The Pisces Overdensity/Stream is located ~ 80 kpc from the Sun at R.A. ~ 355 deg, the trailing arm of the Sagittarius tidal stream (Ivezić et al. 2003) is passing through the stripe 82 plane at (R.A., helio. dist.) = (~ 30 deg, 25 kpc), and the Hercules-Aquila Cloud is located at (~ 330 deg, $\lesssim 25$ kpc). Figure adapted from Sesar et al. (2010a) Fig. 11.

power-law slope of -2.7 (best-fit halo model from Jurić et al. 2008). Fig. 1 shows the comparison of observed and model-predicted number densities on a logarithmic scale. The green regions are in agreement with the smooth halo model, red regions are overdense by a factor of 10, and blue regions are underdense by a factor of 10 compared to the model.

Within about 30 kpc, the observed halo follows the oblate power-law model. Two substructures are clearly visible: the Sgr trailing arm and the Hercules-Aquila Cloud (Belokurov et al. 2007). Beyond 30 kpc, the model predicts more stars than what is actually observed, indicating that the observed number density profile steepens. This steepening is also present when main-sequence stars are used as tracers, as shown in Sesar, Jurić & Ivezić (2011) Figs. 9 and 10 and in Fig. 2 below.

The overdensity seen in Fig. 1 at about 80 kpc was first reported in Sesar et al. (2007) (“J” clump) and was later renamed the Pisces overdensity by Watkins et al. (2009). Kollmeier et al. (2009) and Sesar et al. (2010b) have observed this substructure spectroscopically and have detected two velocity peaks, suggesting that the substructure may be a tidally disrupted dwarf galaxy. A more extended view of this substructure was provided by Sharma et al. (2010) who used M-giants selected from 2MASS.

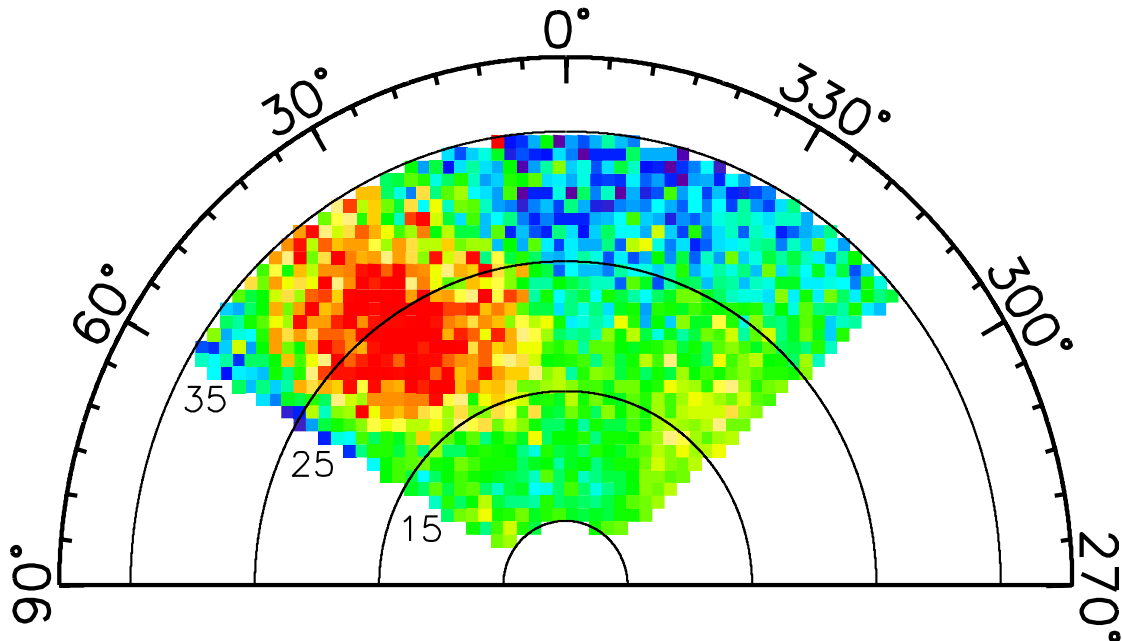


Figure 2.— Halo substructures traced by near turnoff main-sequence stars in SDSS stripe 82. The distance limit in this map is at 40 kpc from the Sun. Note the Sagittarius tidal stream, Hercules-Aquila Cloud, and the steepening of the halo density profile beyond ~ 30 kpc. Figure adapted from Sesar et al. (2010a) Fig. 24.

2.1. A New Photometric Metallicity Method

As shown in Figs. 1 and 2, we have detected the Sagittarius dSph tidal stream (trailing arm) in SDSS stripe 82 as an overdensity of RR Lyrae and main-sequence stars. These detections have allowed us to develop and test a new photometric metallicity method that can be used when SDSS u band observations are not available.

As shown in Fig. 3, for fixed apparent magnitudes, the distance modulus of RR Lyrae and main-sequence stars changes with metallicity, but with opposite signs. For RR Lyrae stars, the distance modulus decreases with increasing metallicity, as dot-dashed lines show. The distance modulus of main-sequence stars, on the other hand, increases with increasing metallicity, as dashed lines show. If we assume that a clump of main-sequence stars belongs to the same substructure as the clump of RR Lyrae stars, we can solve for metallicity and distance modulus. In the case of Sagittarius trailing arm this method gives median metallicity of about -1.2 dex, and agrees well with the median spectroscopic metallicity obtained by Carlin et al. (2010) ($[\text{Fe}/\text{H}] = -1.15$ dex).

The $u-g$ color of main-sequence stars can also be used as an estimator of metallicity, as detailed in Ivezić et al. (2008). Using this method and main-sequence stars in SDSS stripe 82, we estimated -1.2 dex as the metallicity of the Sagittarius trailing arm. However, the Ivezić et al. photometric metallicity method requires $u-g$ observations of main-sequence stars. These observations are difficult to obtain and some current

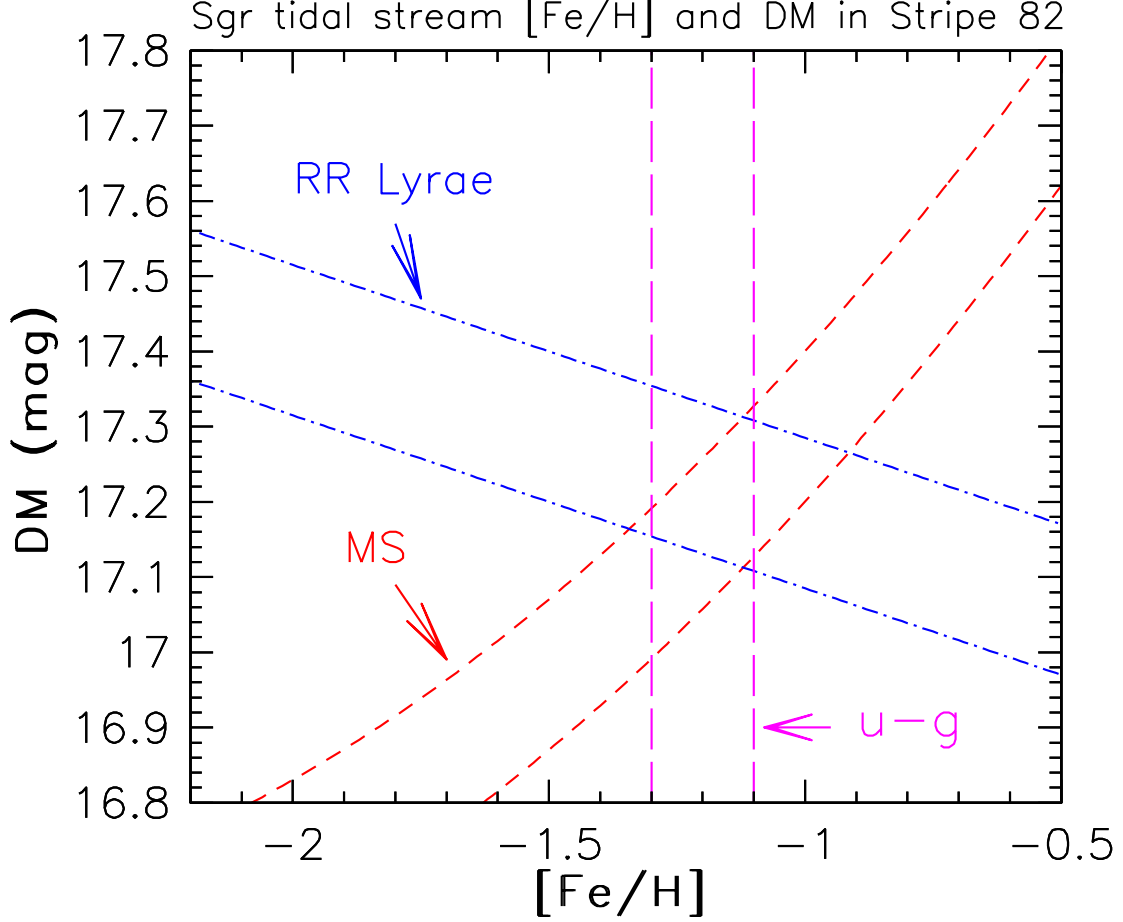


Figure 3.— A summary of the constraints on the distance and metallicity of the Sagittarius dSph tidal stream (trailing arm). The dot-dashed lines show a constraint obtained from the mode of the apparent magnitude distribution of RR Lyrae stars, with ± 0.1 mag adopted as the uncertainty. Diagonal short-dashed lines are analogous constraints obtained from the median apparent magnitude of main-sequence stars with $0.4 < g - i < 0.5$. The vertical longdashed lines mark the median photometric metallicity for main sequence stars obtained using the Ivezić et al. (2008) photometric metallicity method, with ± 0.1 dex adopted as the uncertainty. All three constraints agree if the distance modulus is $DM = 17.2$ mag and $[Fe/H] = -1.2$ dex.

and upcoming sky surveys will not have u -band detections at all. The advantage of the above method is that it does not need u -band observations, and therefore it can be used by surveys such as PTF, PanSTARRS and DES that will not have observations in the u band.

3. Mapping the Galactic Halo with LINEAR and PTF RR Lyrae Stars

The biggest disadvantage of SDSS stripe 82 data is its small sky coverage (only $\sim 1\%$ of the sky), meaning that some of the results and conclusions presented here may not be representative of the entire halo. To address this issue, we have selected about 4000 RRab stars from the LINEAR survey (covering $10,000 \text{ deg}^2$ of sky) and have started to map the Galactic halo in 3D in order to verify the above results based on SDSS stripe 82 data with much smaller sky coverage ($\sim 300 \text{ deg}^2$).

LINEAR stands for the Lincoln Near-Earth Asteroid Research. This ongoing survey (Stokes et al. 2000) has been observing the northern sky since 1998 and is a premier source for variability studies. Unfortunately, detections of asteroids were more important to this survey than photometry so the quality of original data is not as good as in SDSS stripe 82. Following a procedure similar to the one described in Sesar et al. (2006), we have recalibrated LINEAR photometry using SDSS data and have created a database that contains 8.2 million objects with more than 200 observations per object. A sample of about 4000 RRab stars has been selected from this dataset using the selection algorithm from Sesar et al. (2010a). This sample is 90% complete up to 30 kpc, covers $10,000 \text{ deg}^2$ of sky, and the contamination (fraction of non-RR Lyrae stars) is less than 2%.

In order to detect substructures in the region of halo probed by LINEAR RR Lyrae stars, we have applied the *Enlink* group-finding algorithm (Sharma & Johnston 2009) to our sample of LINEAR RRab stars. The Enlink algorithm has identified 6 significant halo groups based only on positions of RR Lyrae stars, and we show these groups in Fig. 5. Even though most of these groups can be associated with globular clusters or known halo streams (e.g., Virgo Stellar Stream; Duffau et al. 2006), the morphology of some groups seems to indicate that they are tidal streams, possibly originating from some of the globular clusters.

Even though the LINEAR survey covers a much wider area of the sky than SDSS stripe 82, it is quite shallow ($r < 18$) and RR Lyrae selected from it probe only the inner part of the Galactic halo (within 30 kpc from the Sun). What is needed is a multi-epoch survey that covers a wide area of the sky and is deep at the same time. The survey that satisfies these criteria and is the Palomar Transient Factory.

PTF is a wide-area, two-band (SDSS- g' and Mould-R filters), deep ($R \sim 21$, single-epoch; $R \sim 23$, co-added) survey aimed at systematic exploration of the optical transient sky. It will provide accurate photometry (with systematic uncertainties $\lesssim 0.02 \text{ mag}$) for more than $10,000 \text{ deg}^2$ of sky in two cadences: i) 5DC – two 60s exposures separated by one hour and repeated after 5 days, and ii) DyC – a dynamical cadence designed to explore transient phenomena on timescales longer than 1 min and shorter than 5 days. These are optimal cadences for the observation of RR Lyrae stars (period of pulsation $\sim 0.6 \text{ days}$) and will ensure a dense phase coverage of light curves. This survey is ongoing and will provide 60 epochs by the end of the survey, enough for an

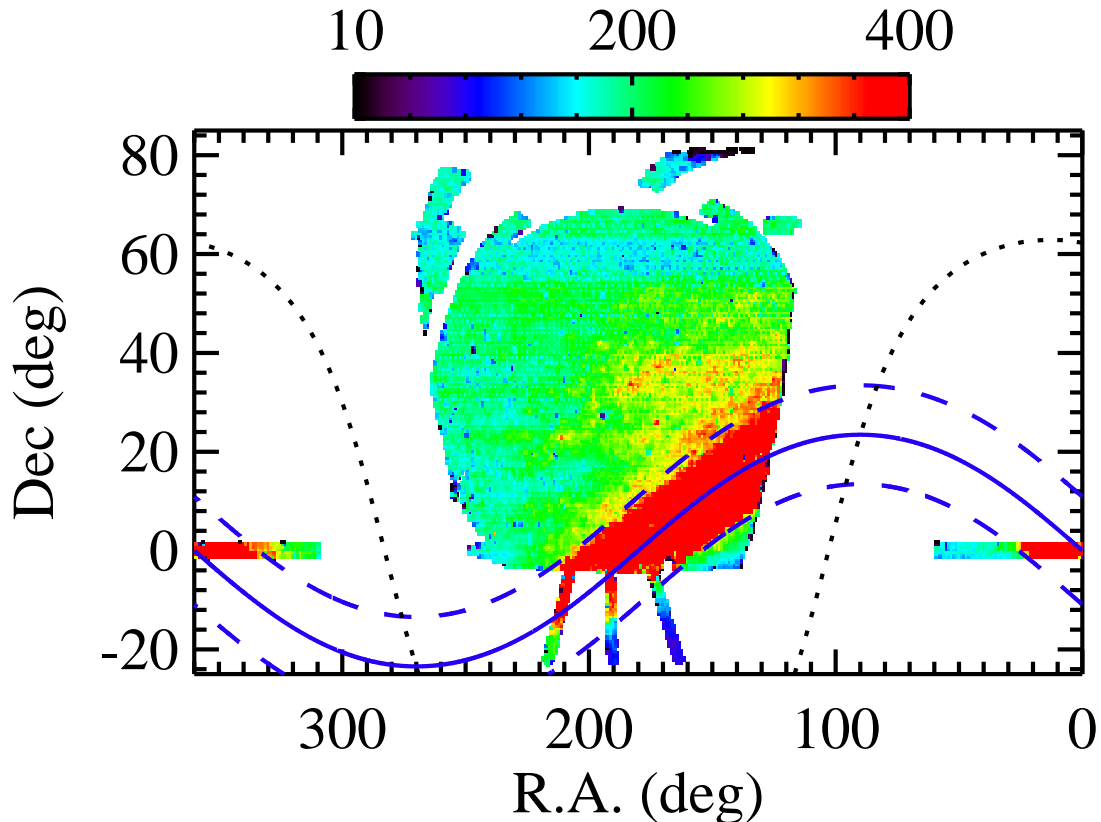


Figure 4.— The median number of observations per object in the recalibrated LINEAR dataset as a function of equatorial J2000.0 right ascension and declination coordinates. The values are color-coded according to the legend, with values outside the range saturating. The dashed lines show $\pm 10^\circ$ of the ecliptic plane (*solid line*) and the Galactic plane is shown as a dotted line. The average number of observations per object within $\pm 10^\circ$ of the ecliptic plane is ~ 460 , and ~ 200 elsewhere.

efficient selection of RR Lyrae stars.

4. Conclusions

We have presented the most complete sample of RR Lyrae stars identified so far in the SDSS stripe 82 data set, consisting of 379 R Rab and 104 R Rc stars. Our visual inspection of single-band and color light curves insures that the sample contamination is essentially negligible. Although the sky area is relatively small compared to other recent surveys, such as Keller et al. (2008) and Miceli et al. (2008), this RR Lyrae sample has the largest distance limit to date (~ 100 kpc).

The high level of completeness and low contamination of our resulting sample, as well as the more precise distance estimates, enabled a more robust study of halo substructure than was possible in our first study. Our main result remains: the spatial distribution of halo RR Lyrae at galactocentric distances 5–100 kpc is highly inho-

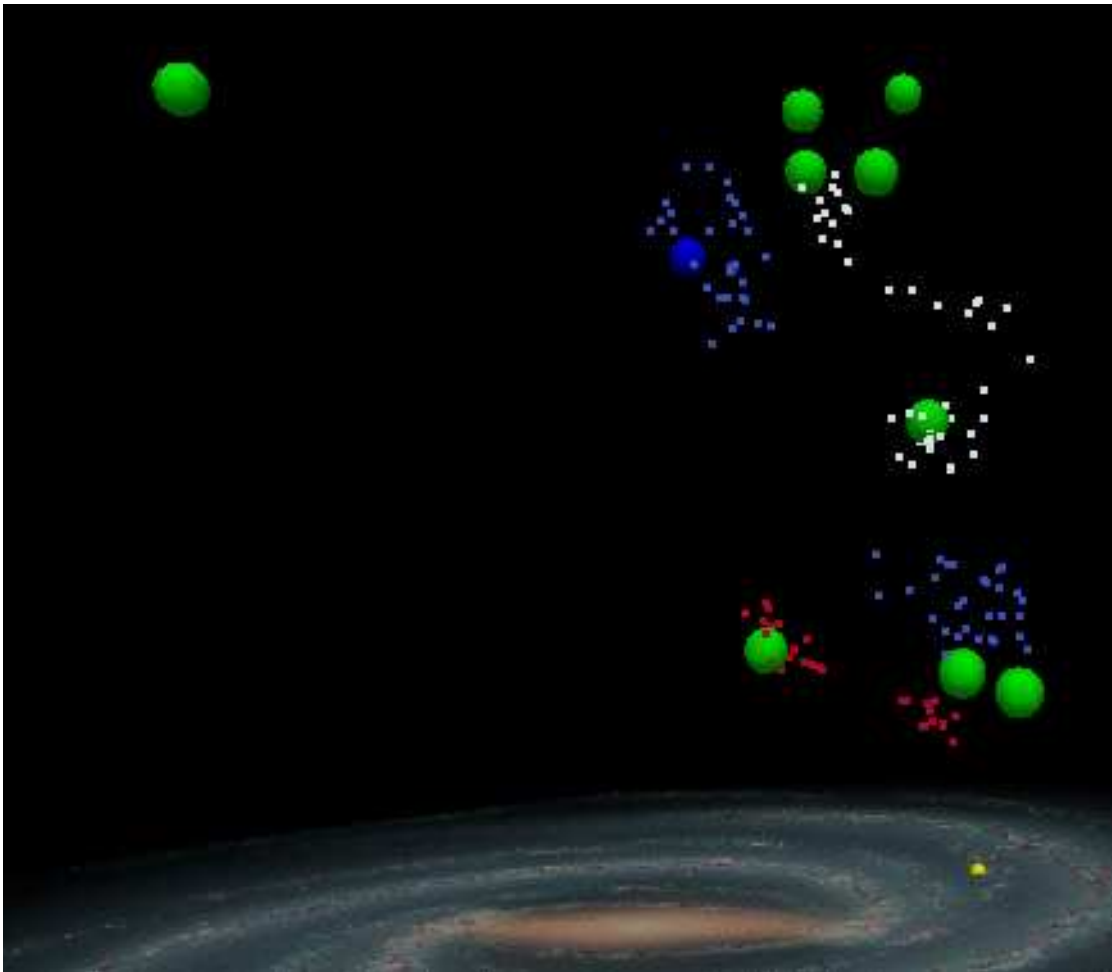


Figure 5.— A 3D rendering of halo substructures detected using LINEAR RRab stars. The points show RRab stars clustered by Enlink into 6 significant groups (there are two red, blue, and white clusters). The Sun’s position in the Galactic disk is indicated by a yellow sphere. The green spheres show positions of some globular clusters and the blue sphere shows the position of the Virgo Stellar Stream according to Duffau et al. (2006). The spatial extent of some groups suggests that they may be tidal streams.

mogeneous. A comparison of the observed spatial distribution of RR Lyrae stars and main sequence stars to the Jurić et al. (2008) model, which was constrained by main sequence stars at distances up to 20 kpc, strongly suggests that the halo stellar number density profile steepens beyond ~ 30 kpc. While various indirect evidence for this behavior, based on kinematics of field stars, globular clusters, and other tracers has been published (Carollo et al. 2007; and references therein), our samples provide a direct measurement of the stellar halo spatial profile beyond the galactocentric distance limit of ~ 30 kpc. A similar steepening of the spatial profile was detected using candidate RR Lyrae stars by Keller et al. (2008).

We introduced a novel method for estimating metallicity that is based on the ab-

solute magnitude vs. metallicity relations for RR Lyrae stars and main sequence stars (calibrated using globular clusters). This method does not require the u -band photometry, and will be useful to estimate metallicity of spatially coherent structures that may be discovered by the Dark Energy and Pan-STARRS surveys. While the existing SDSS data are too shallow to apply this method to the Pisces stream, we used it to obtain a metallicity estimate for the Sgr tidal stream that is consistent with an independent estimate based on the photometric u -band method for main sequence stars. Our result, $[Fe/H] = -1.2$, with an uncertainty of ~ 0.1 dex, strongly rules out the hypothesis that the trailing arm of the Sgr dSph tidal stream has the same metallicity as halo field stars ($[Fe/H] = -1.5$), as suggested by Watkins et al. (2009). Yanny et al. (2009) detected peaks at $[Fe/H] = -1.3$ and at $[Fe/H] = -1.6$ using SDSS spectroscopic metallicities for blue horizontal-branch (BHB) stars from the trailing arm. However, both the Yanny et al. and Watkins et al. results could be affected by systematic errors in the SDSS metallicity scale for BHB stars. Our results suggest that the SDSS metallicity scale for BHB stars could be biased low by about 0.3 dex (relative to the SDSS metallicity scale for main sequence stars, and assuming that RR Lyrae and main sequence stars from the Sgr tidal stream in stripe 82 area have the same metallicity distributions).

Simulations by Bullock & Johnston (2005) and Johnston et al. (2008) predict that there should be a difference in the chemical composition between stars in the inner halo that was built from accretion of massive satellites about 9 Gyr ago, and outer halo dominated by stars coming from dSph satellites that were accreted in the last 5 Gyr (see Fig. 11 in Bullock & Johnston 2005). These accreted dSph satellites were presumably more metal-poor than the massive satellites accreted in earlier epochs (see Fig. 3 in Robertson et al. 2005). Other recent simulation studies support these conclusions. For example, De Lucia & Helmi (2008) find evidence in their simulation for a strong concentration of (relatively) higher metallicity stars at distances close to the Galactic center, and the presence of (relatively) lower metallicity stars at distances beyond 20 kpc from the center. Zolotov et al. (2009) find from their simulations that their inner halos include stars from both in-situ formed stars and accreted populations, while their outer halos appear to originate through pure accretion and disruption of satellites.

Simulations indicate that high surface brightness substructures in the halo originate from single satellites, typically massive dSph which tend to be accreted over the last few Gyr (Bullock & Johnston 2005), and these massive galaxies are expected to be more metal-rich than halo field stars (Font et al. 2008). The results from Ivezić et al. (2008) and the results presented here seem to support this prediction. The inner halo has a median metallicity of $[Fe/H] = -1.5$, while at least two strong overdensities have higher metallicities – the Monoceros stream has $[Fe/H] = -1.0$, and for the trailing part of the Sgr tidal stream we find $[Fe/H] = -1.2$. We emphasize that these three measurements are obtained using the same method/calibration and the same data set, and thus the measurements of relative differences are expected to be robust.

Our result that (inner-) halo stellar number density profile steepens beyond ~ 30 kpc is limited by the relatively small distance limit for main sequence stars (35 kpc), the sparseness of the RR Lyrae sample (~ 500 objects), and the small survey area (~ 300 deg²). Ideally, the halo stellar number density profile should be studied using numerous main sequence stars detected over a large fraction of sky. To do so to a distance limit of 100 kpc, imaging in at least g and r bands (or their equivalent) to a depth several magnitudes fainter than the co-added SDSS stripe 82 data is required ($r > 25$). Pan-STARRS, the Dark Energy Survey and LSST are planning to obtain such data over large areas of sky. The LSST, with its deep u -band data, will also extend metallicity mapping of field main sequence stars over half of the sky in the south; see Ivezić et al. (2008) for details. For substructures to be potentially discovered in the north by Pan-STARRS, the method presented here can be used to estimate the metallicity of spatially coherent structures even without the u -band data.

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